Declining Soil Nutrient Status Can Constrain Agricultural Productivity and Food Security in Pacific Island Countries: A Country Scale Assessment[1]

Gibson Susumu,[2] *Ami Sharma,*[3] *Siosiua Halavatau,*[4] *Diogenes L. Antille,*[5] *Michael J. Webb,*[6] *James Barringer,*[7] *Jennifer Kelly,*[5] *and Ben Macdonald*[5,8]

Abstract: Since human settlement approximately 2,000 years ago, Pacific Island nutrient cycles have been increasingly modified. Modern agricultural intensification has resulted in further changes in the island nutrient flows. Country scale agricultural land nutrient (nitrogen, phosphorus, and potassium) budgeting in Tonga, Fiji, Samoa, Kiribati, and Tuvalu were calculated from FAO country statistic data (1964–2018). Nutrient input data from birds, atmospheric dust, and rainfall and human waste were calculated from literature values. Overall, there are nutrient imbalances in all countries and agricultural lands are exporting nitrogen, phosphorus, and potassium. The budgeting calculations did not consider nutrient losses via erosion, leaching and run-off or denitrification, and the net nutrient fluxes may well be greater than reported. The use of animal and human waste would help off-set nutrient imbalances, but additional macro- and micro-nutrients would need to be added for balanced plant nutrition and soil carbon sequestration. While increasing fertiliser inputs will improve the nutrient balance and potential primary productivity, trade-offs such as nutrient losses will need to be considered. Improving nutrient budgets would need a farming systems approach, whereby the use of cover crops, crop rotations and legumes would augment the fertiliser applications.

Keywords: food and soil security, Guano, nutrient cycling, soil fertility, sustainable intensification of agriculture, tropical soils

Sustainable agriculture is fundamental to the future prosperity of Pacific Island Countries and Territories (PICTs). Commercial farming is an important source of employment and export revenue in several countries (e.g., Fiji, Tonga) and subsistence farming underpins food security for many rural areas. Diverse farming systems operate across the region and range from traditional biodiverse gardening systems (Blanco et al. 2015) through to commercial mechanized cropping systems (van der Velde et al. 2007). Domestic food production is central to the livelihoods of a large proportion of the population in most PICTs (Pushparajah 1989), however, intensification of production is becoming more important due to population growth, tourism, urbanisation, and household income requirements. Development and international agricultural policies and trade, climate change and

[1]Manuscript accepted 8 August 2022.
[2]Secretariat of the Pacific Community, Land Resources Division, Suva, Fiji.
[3]Ministry of Agriculture, Koronivia, Fiji.
[4]Food and Agriculture Organization of the United Nations, Intergovernmental Technical Panel on Soils and Pacific Soil Partnership, Tongatapu, Kingdom of Tonga.
[5]Commonwealth Scientific Industrial Research Organisation, Agriculture and Food, Canberra, ACT, Australia.
[6]Commonwealth Scientific Industrial Research Organisation, Agriculture and Food, Townsville, QLD, Australia.
[7]Landcare Research New Zealand Limited, Lincoln, New Zealand.
[8]Corresponding author (e-mail: Ben.Macdonald@csiro.au).

Pacific Science (2022), vol. 76, no. 3:337–348
doi:10.2984/76.3.7

environmental pressures are threatening the viability of these agricultural systems, particularly on low-lying atolls in countries such as Kiribati, Tuvalu, and the Federated States of Micronesia, and resulting in land degradation across the PICTs (Plahe et al. 2013, Taylor 2016, Wairiu 2016).

Sustainable soil management is a prerequisite for long-term success in agriculture and the nation state. Unfortunately, the recent Status of the World's Soil Resources report (FAO 2015) has found that significant soil degradation has occurred and is limiting agricultural production systems in the Pacific region. Atoll islands are a concern because of increasing population, poor soils, and vulnerable groundwater systems. On volcanic islands land degradation, nutrient imbalances, decline in biological function and very high rates of erosion threaten the viability of current agricultural systems and reduce future management options. Soil degradation, and soil carbon and nutrient decline are leading production constraints that contribute to the observed yield gaps across major food crops in Pacific Island agricultural systems (Antille et al. 2022*a*). Climate change and increased rainfall variability are projected to further compound agricultural production (Kurashima et al. 2019). These soil degradation and nutrient management problems are not new and many of the earlier soil nutrition studies undertaken in the PICTs concluded that soil fertility decline was a pressing issue and a barrier to sustainable and productive agriculture (Demeterto and DeGuzman 1988, Pushparajah 1989, Markham 2013). Soil nutrient management in the PICTs is often contradictory; some systems are low input with soil nutrient decline (O'Sullivan et al. 1993, Craswell et al. 1996) and other more commercial high input systems are causing off-site impacts through leaching and run-off (Van der Velde et al. 2004). A contemporary example of soil nutrient decline has occurred in the sugarcane (*Saccharum officinarum*) systems of Fiji, where the failure to develop farm and soil nutrient budgets and conservation practices has resulted in a decline of soil fertility since the 1980s and has adversely affect productivity (Morrison and Gawander 2016).

Similar soil nutrient imbalances to those developing in the Pacific volcanic and atoll islands have occurred in smallholder farming systems elsewhere in the world (Smaling et al. 1993, Stoorvogel et al. 1993). In Africa, some smallholder farmers have been caught in a poverty trap where crop intensification and declining soil fertility leads to a downward spiral of lowering yields, falling incomes and a decreasing ability to afford the necessary inputs (McCown and Jones 1992, Tittonell and Giller 2013, Urgesa et al. 2016, Adugna et al. 2017). Pacific Island countries and territories must avoid this scenario and improve soil management and maintain fertility. The work reported in this article was conducted to examine the country level soil nutrient budgets for the atoll nations of Tuvalu and Kiribati and the various island types within the Kingdom of Tonga and the volcanic island nations of Fiji and Samoa. This work aims to identify research priorities to inform the development of best management practice (BMP) for soil and soil nutrients.

METHODS

The soil nutrient budgets for the investigated Pacific Islands nations follows the methodology of Stoorvogel et al. (1993), which essentially calculates the nutrient inputs and outputs for a regional area using FAOSTAT datasets (FAO 2020).

Nutrient Additons

Rainfall and Dust — Atmospheric deposition of nutrients (A) from dust and rainfall (kg ha^{-1}) for the Pacific Central Zone was calculated using the area estimated by Gregg et al. (2003) and the nutrient input of 2.8 Tg N yr^{-1} and 0.0039 Tg P yr^{-1} (Okin et al. 2011). The input of K was determined using the N:K elemental ratio from rainfall inputs to a forest catchment in Fiji (Waterloo 1994).

Guano — The input of nutrients from seabirds (*G*) to island ecosystem can be significant (Allaway and Ashford 1984, Anderson and Polis 1998, Young et al. 2010) The nutrient input of seabirds on roosting sites of Heron Island at different population densities was calculated from the Allaway and Ashford (1984) study (Figure 1). Heron Island is a World Heritage Site, which has a national park, a resort and a research station and would represent a relatively undisturbed island. This island can have up to 90,000 roosting and nesting Wedge-tailed Shearwater (*Ardenna pacifica*) on 29 ha Allaway and Ashford (1984).

There are no published studies on the seabird population density during the modern era on developed Pacific Islands. It is clear that the settlement of the Pacific Islands by

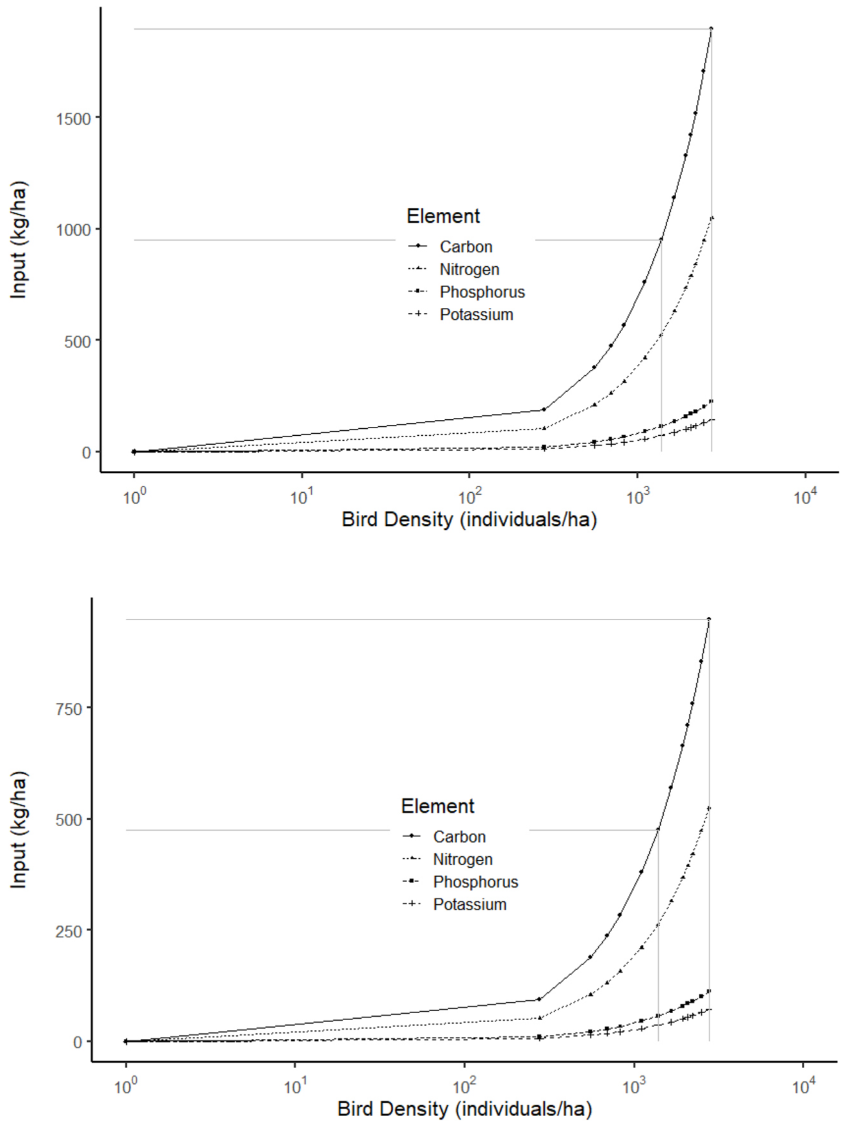

FIGURE 1. Potential annual nutrient input (kg ha^{-1}) as a function of bird density. (*A*) Roosting sites Heron Island, Australia (after Allaway and Ashford 1984). (*B*) Non-roosting sites. Vertical and corresponding horizontal solid grey reference lines represent 50% and 100% bird density and corresponding guano input.

humans has caused significant changes to island ecosystems and seabird populations (Steadman 1995, Steadman 2006). The overrall effect of settlement has been the decline in bird density and increased extinctions. The most significant period was during the initial period of human colonisation but extinctions have continued into the modern era due to increased ecosystem disturbance, increased human population and agricultural intensification.

The developed islands of the Pacific have fewer seabirds due to habitat destruction caused by agricultural development. In this study we have used a seabird density of 6 birds ha^{-1} day^{-1} which is 5% of the bird density (Figure 1*B*) and assumed a non-roosting population nutrient input (Figure 1*B*, Anderson and Polis 1999). The estimated annual nutrient input from seabirds is 1.89 kg C ha^{-1}, 0.38 kg N ha^{-1}, 0.08 kg P ha^{-1} and 0.05 kg K ha^{-1} (Figure 1*B*). Guano N inputs can be lost via volatilisation, denitrification (Mizutani and Wada 1988), run-off and leaching. There is no available data on losses and this study has assumed that 30% of the deposited N is lost via the volatilisation pathway.

Fertiliser, Manure, and Human Waste — Manure (M) from pigs and chickens and fertiliser (F) inputs were calculated from livestock and fertiliser import data (FAO 2020). Human nutrient input (HW) was calculated from FAO human population data and the amount and content of faecal matter produced per person (Rose et al. 2015). At the present time human waste is not used for land-based fertilisation and is not included in Equation 1. Manure N was calculated from the FAO manure data (FAO 2020), and P and K content was calculated on 16:1 stoichiometry in relation to N. The rate of manure use was based on the knowledge of Pacific Island agricultural extension officers. In Kiribati and Tuvalu, 40% of the manure was estimated to be used as a soil amendment, whereas in Tonga, Samoa, and Fiji it is estimated that only 10% is used. There is no available data on nutrient losses, and this was not accounted for in this study.

Outputs

Crop Removal — The amount of nutrients removed by key cropping systems and major crops (Table 1), was calculated from the FAO production statistics and nutrient composition data (FAO 2020).

The annual nutrient removal by cropping (CR) from each agricultural production (kg ha^{-1}) was determined by

$$\mathrm{CR} = \frac{\sum_{\mathrm{Rank}=1}^{5}(Y \times C)}{\mathrm{Area}}, \qquad (1)$$

where Y is the annual yield of the five major crop types within each island and C is the elemental concentration of either N, P and K.

Mass Balance Calculations

The annual nutrient imports (NI, kg ha^{-1}) to each island nation's agriculutral production area was calculated according to Equation 2.

$$\mathrm{NI} = \frac{A + G + F + Mx}{\mathrm{Area}}, \qquad (2)$$

TABLE 1

Crop Types Used to Calculate Nutrient Removal

Country	Commodity
Kiribati	Bananas; taro; coconuts; fruit; vegetables
Tuvalu	Bananas; taro; coconuts; fruit; vegetables
Fiji	Sugarcane; vegetables; bananas; coconut; root crops (taro yam, cassava, & potato)
Tonga	Roots crops (taro, yam, cassava & potato); pumpkins; coconuts; fruit; vegetables; avocado
Samoa	Roots crops (taro, yam, & cassava); coconut; fruits (avocados, mangoes, pineapple, banana, and pawpaw); vegetables

where A is the atmospheric addition of nutrients from rainfall and dust, G is the addition of seabird guano, F is the addition of mineral fertilisers, M is the addition of animal and poultry manures in kg ha^{-1} and x is the proportion of the manure that is utilized. Area represents the agricultural production area as defined by the FAO (FAO 2020).

The mass balance (MB) of nutrient inputs and exports (kg ha^{-1}) was calcaltued using Equation 3,

$$\mathrm{MB} = \mathrm{NI} - \mathrm{CR} \quad (3)$$

If MB is negetative then nutrients are being exported from the agricultural production area.

The potential mass balance (PMB) (kg ha^{-1}) that could be achieved by inclusion nutrients in the human waste streams (HW) and 100% utilisation of animal manures is:

$$\mathrm{PMB} = \mathrm{NI} - \mathrm{CR} + \frac{\mathrm{HW}}{\mathrm{AREA}} \quad (4)$$

The cumulative nutrient input or output was calculated using Equation 4

$$y = \sum_{\mathrm{Year}=1}^{N} (\text{Annual Nutrient Input}), \quad (5)$$

where y is the cumulative nutrient input or output for the nutrient of interest. The time weighted nutrient input, export mass balance (z, kg ha^{-1}) was calculated using Equation 6

$$z = \frac{y_N}{N}, \quad (6)$$

where N is the total number of years used to calculate the total cumulative nutrient input or export (y_N).

RESULTS

Time Weighted Soil Nutrient Budgets

There were soil nutrient in-balances across all the island nations that were investigated (Table 2). Average potassium balance was negative for all the island nations and crop removal exceeded deposition and manure additions on the atolls and fertiliser additions on the volcanic and raised atolls (Table 1). There were no synthetic fertiliser additions in

TABLE 2

Time Weighted Nutrient Additions, Removal and Mass Balance (kg ha^{-1}) for the Agricultural Areas of Kiribati, Tuvalu, Tonga, Fiji and Samoa (1964–2017)

Country	Element	Output Crop Removal	Inputs Deposition	Inputs Fertiliser	Inputs Manures	Mass Balance
Kiribati	N	3.63	1.36	0	0.85	–1.43
	P	0.69	0.23	0	0.18	–0.29
	K	7.6	0.36	0	0.18	–7.06
Tuvalu	N	7.14	1.36	0	8.05	2.27
	P	0.36	0.23	0	1.68	1.55
	K	2.9	0.36	0	1.68	–0.86
Tonga	N	27.58	1.36	4.72	0.65	–20.86
	P	1.11	0.23	0.84	0.13	0.08
	K	14.11	0.36	6.18	0.13	–7.43
Fiji	N	10.17	1.36	1.27	3.31	–4.23
	P	1.31	0.23	0.2	0.69	–0.19
	K	12.41	0.36	0.34	0.69	–11.02
Samoa	N	26.83	1.36	0.11	2.76	–22.61
	P	1.47	0.23	0.04	0.57	–0.63
	K	16.91	0.36	0.07	0.57	–15.91

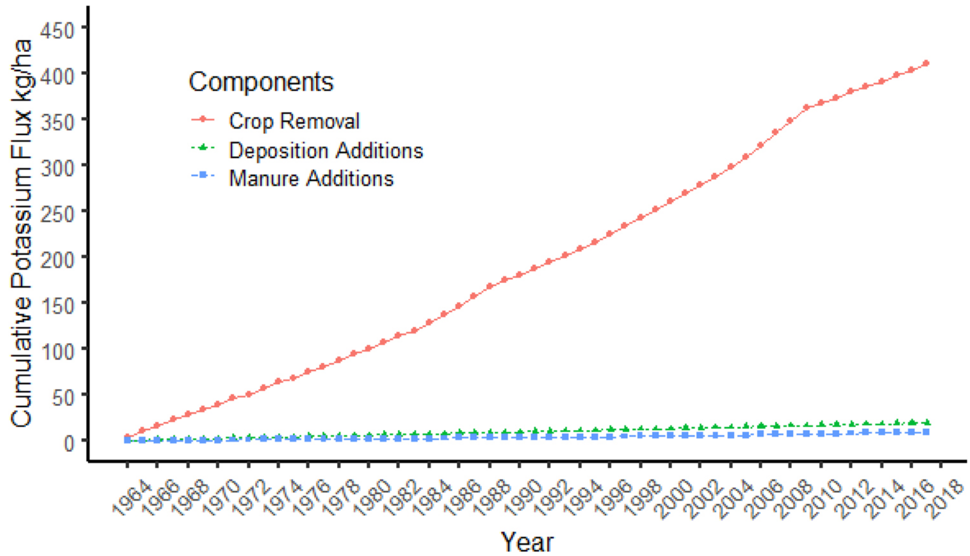

FIGURE 2. Cumulative potassium flux (kg ha^{-1}) crop removal, deposition additions and manure additions (kg ha^{-1}) for Kiribati agricultural area (1964–2017).

TABLE 3

The Potential Average Annual Mass Balance After Utilisation of Livestock and Human Manure (kg ha^{-1}) for Agricultural Area of Kiribati, Tuvalu, Tonga, Fiji, and Samoa (1964–2017).

Country	Element	Output Crop Removal	Inputs Livestock	Human	Total[a]	Mass Balance
Kiribati	N	3.63	2.13	1.06	4.54	0.91
	P	0.69	0.44	0.65	1.32	0.63
	K	7.6	0.44	0.58	1.39	–6.21
Tuvalu	N	7.14	1.36	20.13	9.41	16.87
	P	0.36	0.23	4.19	1.9	5.53
	K	2.9	0.36	4.19	2.04	2.99
Tonga	N	27.58	12.92	1.38	20.37	–7.21
	P	1.11	2.69	0.84	4.6	3.48
	K	14.11	2.69	0.76	10	–4.12
Fiji	N	10.17	11.05	0.81	14.48	4.31
	P	1.31	2.3	0.49	3.23	1.91
	K	12.41	2.3	0.44	3.45	–8.97
Samoa	N	28.25	27.58	2.26	31.3	4.47
	P	1.61	5.75	1.39	7.4	5.93
	K	11.32	5.75	1.25	7.42	–9.49

[a] Deposition and fertilisation.

Kiribati and Tuvalu. Overall, there has been a long-term removal of soil nutrients, as evidenced in Kiribati, over the last 50 years across the studied island nations (Figure 2).

Potential Nutrient Balance

The utilisation of 100% of the human and the animal manure could help to rectify, to varying degrees, the nutrient imbalances within the studied islands (Table 3). The calculation assumes that the nutrient inputs would be uniformly spread across the agricultural areas. The results reveal that despite the additional inputs potassium would still be exported out of the system.

DISCUSSION

Island Budgets

The nutrient balance calculation is based on FAO country statistical data, which is reliant on the submission of accurate data by each country. In some instances, the FAO will estimate data using appropriate methods when country data is missing. The data is only applicable for the agricultural production areas in general and the nutrient flux calculations are based on this area. This assumes a homogenesis nutrient management strategy for all the lands, whereas the strategy will be heterogenous. This means some areas will be over fertilised and some under fertilised.

This study is focused on the macronutrients (N, P, K) and not the micronutrient and base cation imbalances. It is evident from many studies that micronutrient deficiencies (Halavatua et al. 1998) and base cation losses (Sharma 2018) are also prevalent across the Pacific Islands. Micronutrients are also being exported from the agricultural lands and can be a major agricultural production constraint and in some cases the primary cause of the yield gap. The imbalance in NPK is only one aspect of the plant nutrition and should be used to highlight the need to adequately understand the nutrient flows and management of agricultural systems. Furthermore, the importance of organic matter management should not be overlooked. There has been significant carbon loss from Pacific Island farming systems; for example, studies in Fiji and Tonga indicate between 4% and 5% reduction in soil organic carbon (Halavatua et al. 1998, Sharma 2016*b*).

The nutrient balance calculations did not include loss pathways other than nutrient export via the crop and ammonia volatilisation of guano inputs. There are potentially other significant nutrient loss pathways from agricultural lands. It is estimated that erosion rates of up to 50 Mg ha^{-1} yr^{-1} occur on volcanic islands and from storm damage on low-lying atoll islands (FAO 2015). There is also potential for deep leaching, run-off losses and gaseous losses. Currently there are no detailed studies on these nutrient losses. However, it does mean that nutrient balance calculations in this work will underestimate the mass balance deficit at the country scale. Finally, the approach used in this work does not consider the soil NPK bank, but soil fertility is declining in Pacific Island cropping systems (Morrison and Gawander 2016).

Causes of Nutrient Decline in Pacific Islands

Settlement and Ecosystem Disruption — Nutrient inputs from seabirds on PICTs play a key role in terrestrial food webs by transporting marine-based energy and nutrients to islands (Anderson and Polis 1999) and fertilising low input farming systems and terrestrial ecosystems. Sea-levels stabilised in the Pacific Ocean approximately 2,500 years ago (Marshall and Jacobson 1985) and atoll and barrier reef vertical accretion also stabilised. Seabirds can potentially transfer significant amounts of nutrients from the ocean to land on an annual basis (Allaway and Ashford 1984). Land surface and soils would have received nutrients via the deposition of seabird guano inputs and supported plant nutritional requirements. Christmas Island and Nauru represent extreme cases where the phosphate that built up over geological time was exploited for fertiliser (Hutchinson 1950). The input of nutrients via guano causes significantly increased primary productivity on islands (Polis et al. 1997).

The settlement and subsequent agricultural development in the PICTs has resulted in a decrease in nutrient supply from nesting seabirds by extinction, due to habitat destruction and predation (Steadman 2006). This has potentially reduced the ability of the landscape to support complex terrestrial systems and reduced primary productivity (Polis et al. 1997). Human settlement resulted in the disruption of the sea-to-land nutrient flows, decreasing nutrient availability and agricultural intensification depleted nutrients from the islands (Swift et al. 2018). There is a suggestion that the change in terrestrial nutrient dynamics may also impact the primary productivity of the fringing reef system (Morrison et al. 2013).

Agricultural Development — Land degradation has been evident to varying degrees ever since human settlement took place in the Pacific with the initial conversion of forested ecosystems to mixed agro-forestry systems (Kirch 1996). Evidence from Hawai'i indicates that even these low-intensity farming systems resulted in soil nutrient removal through enhanced weathering, increased leaching, and crop removal. This may have caused slow yield declines over a period of about 500 years (Hartshorn et al. 2006). Over time there has been a conversion of traditional agroforestry systems with typically long fallows, to systems with shortened fallows, and eventually to more intensive systems. Typically, these steps have been made without adequate fertilisation and have resulted in widespread falling productivity (Sharma 2016*b*). While there is some uncertainty about the effect that shortened fallows have on soil nutrient cycling in humid tropical shifting agriculture (Mertz 2002), there is ample evidence to show that nutrient inputs are required to maintain and, where possible, increase yields in agricultural farming systems (e.g., Angus and Peoples 2012).

In all intensive farming systems, the end-point of this continuum is continuous cultivation of the same piece of land, which leads to nutrient depletion (via crop harvest, erosion, and oxidation of organic matter), and therefore progressive yield decline. Soil fertility decline is a major production constraint and has been identified as a high research priority in taro agricultural systems (Onwueme 1999, Antille et al. 2022*a*).

The nutrients budget analysis (Table 2) indicates that there is inadequate NPK fertilisation in the agricultural production areas of Tuvalu, Tonga, Kiribati, Fiji, and Samoa. Other field-based studies have found that the depletion of soil NPK levels have contributed to the yield decline of agricultural production, such as taro and sweet potato (e.g., Halavatua et al. 1998, Sharma 2016*a*, Antille et al. 2022*b*) across many Pacific Island nations.

Governance and Economic Barriers — Fijian taro farmers have identified that access to market, instability of market prices, transport, grower capability, production cost and agronomic supplies are production constraints which effect production profitability (Sharma 2016*a*). Plahe et al. (2013) have shown that when institutional arrangements prevent access to markets agricultural development and access to capital are stifled. These underlying microeconomic issues appear to be preventing farmers from utilizing synthetic and organic fertilisers to halt fertility decline. This assertion requires investigation because the cause of these barriers may be complex and involve individual perceptions of risk, market inefficiencies, post-harvest losses, access to information and other institutional factors.

On atoll islands, such as Tuvalu and Kiribati, the soils are relatively infertile compared to those on the volcanic islands and have also lost soil nutrients due to tillage, deep drainage, crop export, and reduction of nutrient inputs due to the decline in seabird population. While the potential for high-value crop exports from atolls is limited, production of fruit and vegetables for local urban markets is an important source of cash income for the underprivileged poor (White et al. 2007). There are no quick fixes, and the rapid rollout and application of fertilisers is not the solution. Agricultural production is a key source of N and faecal contamination of ground water lenses (van der Velde et al.

2007, White and Falkland 2010). This has led to widespread restrictions on the use of synthetic fertilisers in many atoll nations and the subsequent development of organic agricultural production systems. Typically, organic nutrients are sourced from the household domestic kitchen wastes, but material is also collected from other locations such as forest and bush reserves, harvested seaweed, driftwood, and tide wrack. This harvesting of these source areas needs to be carefully managed so that nutrients are not mined, and systems are maintained. None-the-less the same issues still face organic growers in terms of nutrient management to maximise profitability and existing soil nutrient imbalances, poor soil health and the protection of ground water resources.

Implications and Solutions — The under-fertilisation of agricultural lands of the Pacific Islands countries and territories is not unique and is an issue thorough out the world (Silver et al. 2021). In the Pacific Islands the nutrient and protein content of traditional food crops, such as taro, have been shown to be correlate with the mineral content of the soil (Bradbury and Holloway 1988). Nutritional deficiency in food can originate in soil nutrient limitations, and in the Pacific, this is evident in several regions and is reflected in human health (Bradbury and Holloway 1988, Lyons et al. 2020). Improved agricultural macro and micro-nutrient management is required not only to increase yield but nutritional food content. The measurement of nutrient flows through the Pacific Island food system is required to address human and livestock nutrition management.

There is potential to improve the nutrient balance in agricultural soils using treated human and animal wastes in the countries studied. While technical and cultural aspects of waste utilisation need to be solved, waste represents a potential source of agriculture fertiliser. However, there would still be a need to fortify the recycled waste with additional macro- and micro-nutrients for each soil and farming system to ensure a balanced nutrient replenishment program. Additionally, the use of diverse deep and shallow rooted cover crops and legumes would improve soil health and soil carbon stocks. There is a need for governments and industry to develop programs that improve landowner knowledge of nutrient budgeting, the long-term implications of poor nutrient management on food and soil security, and options to improve soil and nutrient management. The measurement of nutrient flows through the Pacific Island food system is required to address human and livestock nutrition management

CONCLUSIONS

Country nutrient budgets reveal that on the islands of Kiribati, Tonga, Samoa, Fiji, and Tuvalu that agricultural lands are not adequately fertilised with NPK. This constant NPK export is contributing to yield decline, and soil and food system insecurity. The budgeting in this paper did not examine micronutrient and base cation export, but it could be expected that similar imbalances also occur and would be contributing to the measured yield gaps. The causes of soil fertility decline are varied, and different solutions will need to be culturally, environmentally, and economically relevant. A rapid blanket roll-out of synthetic fertilisers to correct agricultural nutrient management is not a solution. The first step is development nutrient budgeting for specific soil types and farming systems to identify the appropriate broad-based solutions. Farming systems will need to include crop rotations and tillage and residue management that increase soil health. Finally, biophysical data should be a capture and used to guide improved management by landholders through to policy makers.

ACKNOWLEDGEMENTS

This work was undertaken and funded through two Australian Centre for International Agricultural Research grants (SMCN/2016/111 and SMCN/2014/021).

Literature Cited

Adugna, A., A. Abegaz, A. Legass, and D. L. Antille. 2017. Random and systematic land-cover transitions in north-eastern Wollega, Ethiopia. Bois For. Trop. 332:3–15.

Allaway, W. G., and A. E. Ashford. 1984. Nutrient input by seabirds to the forest on a coral island of the Great Barrier Reef. Mar. Ecol. Prog. Ser. 19:297–298.

Anderson, W. B., and G. A. Polis. 1998. Marine subsidies of island communities in the Gulf of California: evidence from stable carbon and nitrogen isotopes. Oikos 81(1): 75–80.

———. 1999. Nutrient fluxes from water to land: seabirds affect plant nutrient status on Gulf of California islands. Oecologia 118(3):324–332.

Angus, J. F., and M. B. Peoples. 2012. Nitrogen from Australian dryland pastures. Crop Pasture Sci. 63:746–758.

Antille, D. L., D. J. Field, S. M. Halavatau, E. T. Iramu, B. C. T. Macdonald, K. Singh, and M. J. Webb. 2022*a*. Regional soil priorities creating partnerships with Australia and New Zealand across the Pacific. Geoderma Reg. 29, Article number e00517.

Antille, D. L., A. Uelese, A. Tugaga, M. J. Webb, S. Tauati, J. Kelly, U. Stockmann, J. Barringer, J. Palmer, and B. C. T. Macdonald. 2022*b*. Agronomic response of rainfed taro to improved soil and nutrient management practices in Samoa. ASABE Paper No.: 2200065. 2022 ASABE Annual International Meeting, American Society of Agricultural and Biological Engineers, St. Joseph, MI. https://doi.org/10.13031/aim.202200065

Blanco, J., H. Vandenbroucke, and S. M. Carrière. 2015. A novel index to quantify agrobiodiversity in a biocultural perspective: the case of shifting cultivation gardens in Vanuatu Pacific. Agroecol. Sustain. Food Syst. 40:190–214.

Bradbury, J. H., and W. D. Holloway. 1988. Chemistry of tropical root crops: significance for nutrition and agriculture in the Pacific. ACIAR Monograph No. 6, pp. 201. Accessed July 2022. https://www.aciar.gov.au/publication/books-and-manuals/chemistry-tropical-root-crops-significance-nutrition-and-agriculture-pacific

Craswell, E. T., C. l. Asher, and L. N. O'Sullivan. 1996. Mineral nutrient disorders of root crops in the Pacific. Proceedings of a Workshop, Nuku'alofa, Kingdom of Tonga, 17–20 April 1995, pp. 145. ACIAR, Canberra, ACT, Australia.

Demeterto, J. L., and B. DeGuzman. 1988. Proceedings of the Third International Soil Management Workshop: Management and Utilization of Acid Soils of Oceania, pp. 338. Belau, Republic of Palau, February 2–6, 1987. Agricultural Experiment Station, College of Agriculture and Life Sciences, University of Guam. Accessed July 2022. http://opac.spc.int/cgi-bin/koha/opac-detail.pl?biblionumber=53971

FAO. 2015. Status of the World's Soil Resources: Main Report, pp. 650. Prepared by The Global Soil Partnership and Intergovernmental Technical Panel on Soils (ITPS). Food and Agriculture Organization of the United Nations, Roma, Italy. Accessed July 2022. https://www.fao.org/documents/card/en/c/c6814873-efc3-41db-b7d3-2081a10ede50/

———. 2020. FAOSTAT. https://www.fao.org/faostat/en/#home

Gregg, W. W., M. E. Conkright, P. Ginoux, J. E. O'Reilly, and N. W. Casey. 2003. Ocean primary production and climate: global decadal changes. Geophys. Res. Lett. 30(15):1–4.

Halavatau, S. M., J. N. O'Sullivan, C. J. Ashr, and F. P. C. Blamey. 1998. Better nutrition for improvement of sweetpotato and taro yields in the South Pacific. Trop. Agric. 75(1–2):6–12.

Hartshorn, A. S., O. A. Chadwick, P. M. Vitousek, and P. V. Kirch. 2006. Prehistoric agricultural depletion of soil nutrients in Hawai'i. Proc. Natl. Acad. Sci. 103(29): 11092–11097.

Hutchinson, G. E. 1950. Survey of existing knowledge of biogeochemistry. 3, The biogeochemistry of vertebrate excretion. Bull. Am. Mus. Nat. Hist. 96:596.

Kirch, P. V. 1996. Late Holocene human-induced modifications to a central Polynesian island ecosystem. Proc. Natl. Acad. Sci. U. S. A. 93(11):5296–5300.

Kurashima, N., L. Fortini, and T. Ticktin. 2019. The potential of indigenous agricultural food production under climate change in Hawai i. Nat. Sustain. 2:191–199.
Lyons, G., G. Dean, R. Tongaiaba, S. Halavatau, K. Nakabuta, M. Lonalona, and G. Susumu. 2020. Macro- and micronutrients from traditional food plants could improve nutrition and reduce non-communicable diseases of Islanders on Atolls in the South Pacific. Plants 9(8): 1–15. Article number 942.
Markham, R. 2013. The paradox of horticulture in the Pacific Islands. Chron. Horticult. 53:14–20.
Marshall, J. F., and G. Jacobson. 1985. Holocene growth of a mid-Pacific atoll: Tarawa, Kiribati. Coral Reefs 4:11–17.
McCown, R. L., and R. K. Jones. 1992. Agriculture of semi-arid eastern Kenya: problems and possibilities. In: M. E. Probert, ed. Proceedings of a Symposium Held in Nairobi, Kenya, 10–11 December 1990: 'A Search for Strategies for Sustainable Dryland Cropping in semi-arid Eastern Kenya'. Australian Centre for International Agricultural Research, Canberra, ACT, Australia.
Mertz, O. 2002. The relationship between length of fallow and crop yields in shifting cultivation: a rethinking. Agrofor. Syst. 55:149–159.
Mizutani, H., and E. Wada. 1988. Nitrogen and carbon isotope ratios in seabird rookeries and their ecological implications. Ecology 69:340–349.
Morrison, R. J., G. R. W. Denton, U. B. Tamata, and J. Grignon 2013. Anthropogenic biogeochemical impacts on coral reefs in the Pacific Islands – an overview. Deep Sea Res. II: Top. Stud. Oceanogr. 96:5–12.
Morrison, R. J., and J. S. Gawander. 2016. Changes in the properties of Fijian Oxisols over 30 years of sugarcane cultivation. Soil Res. 54:418–429.
Okin, G. S., A. R. Baker, I. Tegen, N. M. Mahowald, F. J. Dentener, R. A. Duce, J. N. Galloway, K. Hunter, M. Kanakidou, N. Kubilay, J. M. Prospero, M. Sarin, V. Surapipith, M. Uematsu, and T. Zhu. 2011. Impacts of atmospheric nutrient deposition on marine productivity: roles of nitrogen, phosphorus, and iron. Global Biogeochem. Cycles 25:GB2022, https://doi.org/10.1029/2010GB003858
Onwueme, I. 1999. Taro cultivation in Asia and the Pacific. RAP Publication: 1999/16, pp. 60. Food and Agriculture Organization of the United Nations, Regional Office for Asia and the Pacific, Bangkok, Thailand.
O'Sullivan, J. N., C. J. Asher, F. P. C. Blamey, and D. G. Edwards. 1993. Mineral nutrient disorders of root crops of the Pacific: preliminary observations on sweet potato (*Ipomoea batatas*). Plant Soil 155:263–267.
Plahe, J. K., S. Hawkes, and S. Ponnamperuma. 2013. The corporate food regime and food sovereignty in the pacific islands. Contemp. Pac. 25:309–338.
Polis, G. A., A. J. Anderson, and R. D. Holt. 1997. Toward an integration of landscape and food web ecology: the dynamics of spatially subsidized food webs. Annu. Rev. Ecol. Syst. 28:289–316.
Pushparajah, E. 1989. Soil management and smallholder development in the Pacific Islands: Pacificland. IBSRAM Proceedings No.: 8, pp. 304. IBSRAM, Bangkok, Thailand. ISBN: 9747613204.
Rose, C., A. Parker, B. Jefferson, and E. Cartmell 2015. The characterization of feces and urine: a review of the literature to inform advance treatment technology. Crit. Rev. Sci. Technol. 45:1827–1879.
Sharma, A. C. 2016*a*. Intensive taro *Colocasia esculenta* cultivation and soil dynamic on volcanic Anddosols of Taveuni, Fiji. Fiji Agric. J. 56:31–36.
———. 2016*b*. Soil fertility and productivity decline from twenty-two years of intensive taro cultivation in Taveuni, Fiji. MSc Thesis, The University of the South Pacific.
———. 2018. Soil fertility and productivity decline resulting from twenty two years of intensive taro cultivation in Taveuni, Fiji. Fiji Agric. J. 57:50–58.

Silver, W. L., T. Perez, A. Mayer, and A. R. Jones 2021. The role of soil in the contribution of food and feed. Philos. Trans. R. Soc. B: Biol. Sci. 376 (1834):20200181.

Smaling, E. M. A., J. J. Stoorvogel, and P. N. Windmeijer. 1993. Calculating soil nutrient balances in Africa at different scales. 2. District scale. Fertil. Res. 35:237–250.

Steadman, D. 1995. Prehistoric extinctions of Pacific Island birds: biodiversity meets zooarchaeology. Science (5201):1123–1131.

Steadman, D. W. 2006. Extinction and biography of tropical birds. University of Chicago Press, Chicago, IL, pp. 480. ISBN: 978-0226771427.

Stoorvogel, J. J., E. M. A. Smaling, and B. H. Janssen 1993. Calculating soil nutrient balances in Africa at different scales. 1. Supra-national scale. Fertil. Res. 35:227–235.

Swift, J. A., P. Roberts, N. Boivin, and P. V. Kirch. 2018. Restructuring of nutrient flows in island ecosystems following human colonization evidenced by isotopic analysis of commensal rats. Proc. Natl. Acad. Sci. U. S. A. 115(25):6392–6397.

Taylor, M. 2016. PACC Demonstration Guide: Piloting climate change adaptation in food production and food security on low-lying atolls of Solomon Islands. PACC Technical Report No.: 19, pp. 44. SPREP, Apia, Samoa. ISSN: 2312-8224.

Tittonell, P., and K. E. Giller. 2013. When yield gaps are poverty traps: the paradigm of ecological intensification in African smallholder agriculture. Field Crops Res. 143:76–90.

Urgesa, A. A., A. Abegaz, A. L. Bahir, and D. L. Antille. 2016. Population growth and other factors affecting land-use and land-cover changes in north-eastern Wollega, Ethiopia. Trop. Agric. 93(4):298–311.

Van der Velde, M., S. Green, G. W. Gee, B. Clothies, B. Snow, V. Manu, V. Menoniti, and M. Vanclooster. 2004. Flux meters for quantifying the leaching of agrichemicals on the island of Tongatapu, the Kingdom of Tonga, pp. 5. Supersoil 2004, Symposium 16: Water Quality and Soil Management. 3rd Australian New Zealand Soils Conference, 5–9 December 2004. University of Sydney, Australia. Accessed July 2022. http://www.regional.org.au/au/asssi/supersoil2004/s16/oral/1451_clothierb.htm

van der Velde, M., S. R. Green, M. Vanclooster, and B. E. Clothier. 2007. Sustainable development in small island developing states: agricultural intensification, economic development, and freshwater resources management on the coral atoll of Tongatapu. Ecol. Econ. 61:456–468.

Wairiu, M. 2016. Land degradation and sustainable land management practices in Pacific Island countries. Reg. Environ. Change 17:1053–1064.

Waterloo, M. J. 1994. Water and nutrient dynamics of *Pinus caribaea* plantation forests on former grassland soils in Southwest Viti Levu, Fiji. PhD Thesis, Vrije Universiteit Amsterdam. ISBN: 90900 72926.

White, I., and T. Falkland. 2010. Management of freshwater lenses on small Pacific islands. Hydrogeol. J. 18:227–246.

White, I., T. Falkland, P. Perez, A. Dray, T. Metutera, E. Metai, and M. Overmars. 2007. Challenges in freshwater management in low coral atolls. J. Clean. Prod. 15:1522–1528.

Young, H. S., D. J. McCauley, R. B. Dunbar, and R. Dirzo. 2010. Plants cause ecosystem nutrient depletion via the interruption of bird-derived spatial subsidies. Proc. Natl. Acad. Sci. 107(5):2072–2077.